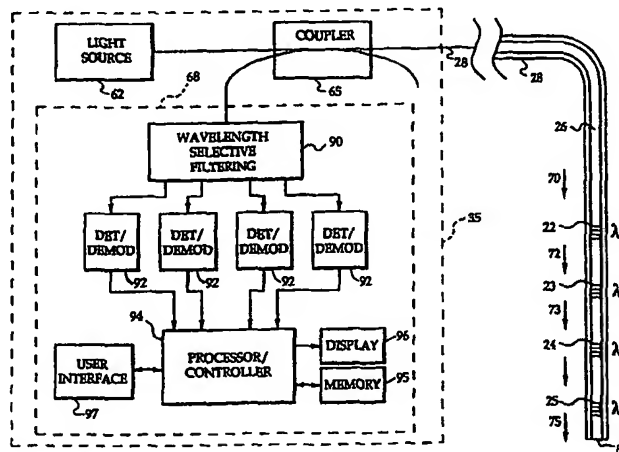




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(54) Title: FIBER OPTIC BRAGG GRATING SENSOR SYSTEM FOR USE IN VERTICAL SEISMIC PROFILING



(57) Abstract

A system for vertical seismic profiling of an earth borehole includes an optical fiber (28) having a plurality of Bragg grating sensors (22-25) formed therein, each one of the Bragg grating sensors (22-25) being tuned to reflect a respective bandwidth of light, each bandwidth having a different respective central wavelength. Each of the Bragg grating sensors (22-25) are responsive to an input light signal, a static strain, a dynamic strain and a temperature strain for each providing a respective light signal indicative of static and dynamic forces and temperature at a respective sensor location. The physical spacing and wavelength spacing of the Bragg grating sensors (22-25) are known such that each of the sensing light signals are easily correlated to a specific depth. The Bragg grating sensors (22-25) are tuned such that when a sensor is subjected to a maximum static strain, maximum dynamic strain, and a maximum temperature strain, the maximum wavelength shift of a respective sensing light signal does not cause the frequency of the sensing light signal to enter the bandwidth of another one of the plurality of Bragg grating sensors (22-25).

FIBER OPTIC BRAGG GRATING SENSOR SYSTEM FOR USE IN VERTICAL SEISMIC PROFILING

TECHNICAL FIELD

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The present invention relates to fiber optic sensing, and more particularly, to a fiber optic Bragg grating sensor system for use in vertical seismic profiling.

BACKGROUND OF THE INVENTION

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Vertical seismic profiling (VSP) is a method of determining acoustic wave characteristics of rock layers in situ. The method includes lowering one or more sensors into a wellbore to a preselected depth. Typically several sensors are spaced apart to allow coverage over a preselected depth interval. A seismic signal is
15 generated at or near the surface of the earth and propagates through the earth to be received by the sensors. These sensors convert the acoustic energy to sensing signals which are transmitted to the surface for suitable processing and recording.

20

U.S. Patent No. 4,589,285 to Savit issued on May 20, 1996 discloses a vertical seismic profiling arrangement using optical fiber sensors. In particular, the disclosed system includes an elongated cable having a bi-directional optical fiber transmission link therein. A plurality of acousto-optic seismic sensors, each consisting of one- or multi-turn optical fiber coils, are coupled to the optical fiber transmission length by means of suitable directional optical couplers. The optical fiber coil making up each
25 sensor acts as a resonant optical cavity to certain discrete wavelengths, as a function of the local static pressure environment within the borehole fluid. The resonant discrete wavelength under static conditions is the center or reference wavelength. Under dynamic conditions, the reference wavelength is data modulated (wavelength shifted) by transient pressure variations due to acoustic or seismic signals.

division multiplex basis wherein return signals from various Bragg gratings in the sensor string are uniquely identified by their position in a pulse train of signals, such as disclosed in U.S. Patent No. 5,361,130. Alternatively, as disclosed in U.S. Patent No. 5,401,956, each Bragg grating sensor may have a central reflection wavelength
5 different from that of the other fiber Bragg gratings such that the signals reflected by the Bragg grating sensor string are uniquely identified based on the wavelength of the received signals in a wavelength division multiplex system.

While such distributed fiber Bragg grating sensor systems have been utilized
10 for distributed sensing of strain, temperature or other perturbations, such sensor systems have not been utilized for vertical seismic profiling in an earth borehole. In particular, as described above, an earth borehole of an oil or gas well presents an extremely hostile environment because of the high temperature, pressure and
corrosive environment.

15

There therefore exists a need for an improved system for vertical seismic profiling of an earth borehole which provides highly accurate and reliable indication of seismic conditions while at the same time being resistant to the extremely hostile environment of an earth borehole.

20

SUMMARY OF THE INVENTION

Objects of the invention include the provision of a system for vertical seismic profiling of an earth borehole utilizing Bragg grating sensors.

25

A further object of the present invention is to provide such a sensing system which is suitable for vertical seismic profiling over a long depth within an earth borehole and which provides accurate and reliable seismic profiling information which is easily correlated to specific depths.

30

while at the same time providing a reliable and accurate indication of the seismic signals of interest.

5 The foregoing and other objects, features, and advantages of the present invention will become more apparent in light of the following detailed description of exemplary embodiments thereof, as illustrated in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

10 Fig. 1 is a cross-sectional view of an earth borehole having a Bragg grating sensor string of the invention deployed therein for vertical seismic profiling;

Fig. 2 is a more detailed schematic block diagram of the Bragg grating sensor string of Fig. 1;

Fig. 3 is a graph showing the reflectivity profile of four Bragg grating sensors;

15 Fig. 4 is a schematic block diagram of a second embodiment of the Bragg grating sensor string of Fig. 1; and

Fig. 5 is a schematic block diagram of a third embodiment of the Bragg grating sensor string of Fig. 1.

DETAILED DESCRIPTION OF THE DRAWINGS

20 Referring to Fig. 1, a borehole 10, such as an oil or gas well, penetrates various earth layers 12, 14, 16. Such a borehole may be fifteen to twenty thousand feet or more in depth. As is known in the art, the borehole is filled with a high
25 temperature and pressure drilling fluid 18 which presents an extremely corrosive and hostile environment.

An optical fiber sensor string 20 includes Bragg grating sensor elements 22, 23, 24, 25 formed within a core 26 (Fig. 2) of an optical fiber 28. The optical fiber 28
30 is positioned within a capillary tube 30.

as 3,000 feet.

In an alternative embodiment of the invention, the fiber may be provided to extend the entire length of the well, e.g., 15,000 to 20,000 feet, with the Bragg grating sensors 22, 23, 24, 25 evenly spaced at desired intervals along the length of the fiber. The sensors may be provided as a single WDM set as illustrated in Figs. 1 and 2. Alternatively, as illustrated in Fig. 5, a plurality of WDM sets 241, 242, 243 may be combined by Time Division Multiplexing (TDM) sets of the WDM sets. For example, for a 20,000 foot well, 400 sensor points are required for a sensor spacing of 50 feet. This may be achieved for example by a single WDM set of sensors. Alternatively, four sets of sensors each containing 128 WDM sensors may be TDM together for a total of 512 sensors. In this case, a spacing of less than 40 feet between sensors can be used.

Returning to Fig. 2, acoustic waves radiate from the shot along a direct path 52 and a reflected path 54. The reflected waves 54 are reflected off of the various earth layers 12, 14, 16. As will be described in greater detail hereinafter, the direct seismic waves 52 and reflected seismic waves 54 are detected by the sensors 22, 23, 24, 25. Resulting data signals are transmitted through the optical fiber 28 to the optical signal processing equipment 35. In one embodiment of the invention, after the seismic shot, the optical sensor string 20 is repositioned within the borehole for additional seismic profiling. In a second embodiment of the invention, the Bragg grating sensors 22, 23, 24, 25 are distributed over the entire length of the optical fiber 28 such that the entire borehole 10 is characterized in a single shot. In order to improve the transmission of acoustic signals through the capillary tube 30 to the Bragg grating sensors 22, 23, 24, 25 the capillary tube 30 may be filled with a high-density low-compressibility material 60, such as the material disclosed in commonly owned co-pending U.S. Patent Application Serial No. 08/777,271 filed on December 31, 1996, the disclosure of which is incorporated herein by reference.

30

matches the index of refraction of the fiber, thus permitting the light 75 to exit the fiber without back reflection, and be subsequently dispersed in the index-matching material.

5 Referring to Fig. 4, in another embodiment of the invention, rather than terminating the optical fiber in an anti-reflective manner, the optical fiber 128 may be looped back to the surface within the tube 130. The portion of the fiber 140 returning to the surface may or may not have gratings in it. This return fiber portion 140 may be used to check for fiber integrity by monitoring the entire loop at the optical signal
10 processing equipment 135 to ensure that there are no breaks or degradation of the fiber. Changes in the light not reflected by any of the Bragg gratings and returned to the surface by the return fiber portion 140 may be monitored 145 to detect problems with the fiber. Therefore, variations in the sensor return signals caused by problems with the fiber are easily differentiated from changes in the return signals associated
15 with strain caused by temperature and static and dynamic pressure.

Referring also to Figs. 1 and 3, the fiber Bragg gratings 22, 23, 24, 25 will experience strain due to several environmental factors including temperature, static pressure associated with the column of noncompressible fluid 60 within the capillary
20 tube 30, and acoustic pressure associated with the seismic waves 52, 54. As discussed above, these strains will cause a wavelength shift in the central wavelength of the narrow band of light reflected by each Bragg grating sensor. For example, when the first Bragg grating sensor 22 is subjected to the static strain (from the static pressure of the noncompressible fluid) the dynamic strain (from the seismic waves) and the
25 temperature strain, the central wavelength λ_A shifts by an amount $\Delta\lambda_A$ to a new central wavelength λ_A' . Each of the Bragg grating sensors 22, 23, 24, 25 are designed to provide a wavelength spacing such that when the central wavelength of one of the Bragg grating sensors shifts by a maximum amount associated with a maximum dynamic, static and temperature strain, the central wavelength will still be in a desired
30 bandwidth ω which does not overlap with any of the other Bragg grating sensors.

The output of the sensitive wavelength or phase discrimination equipment 92 is provided to a processor/controller 94 for processing, storage in memory 95, display 96 to a user, or for any other desired use. The processor 94 may be provided with a
5 user interface 97 for user input and control, for example to generate reports illustrating the results of the vertical seismic profiling.

As will be understood by those skilled in the art, the wavelength selective filtering includes wavelength division demultiplexer which is used to separate the
10 wavelength components onto separate fibers which are then each analyzed via separate high resolution wavelength discriminators. An example of the type of wavelength discrimination suitable for this purpose is the interferometric detection approach described in U.S. Patent No. 5,361,130, the disclosure of which is incorporated herein by reference.

15

Although a specific embodiment of the optical signal processing equipment is described above, other optical signal analysis techniques may be used with the present invention such as the necessary hardware and software to implement the optical signal diagnostic equipment disclosed in U.S. Patent Nos. 4,996,419; 5,401,956; 5,426,297;
20 and/or 5,493,390, the disclosures of which are incorporated herein by reference.

As is well known in the art, there are various optical signal analysis approaches which may be utilized to analyze return signals from Bragg gratings. These approaches may be generally classified in the following four categories:

25

1. Direct spectroscopy utilizing conventional dispersive elements such as line gratings, prisms, etc., and a linear array of photo detector elements or a CCD array;
2. Passive optical filtering using both optics or a fiber device with wavelength-dependent transfer function, such as a WDM coupler;
- 30 3. Tracking using a tuneable filter such as, for example, a scanning Fabry-

equipment 252 is utilized to differentiate between the signals provided by each set of sensors. This arrangement provides certain advantages. The same optical signal processing equipment 235 may be utilized to analyze the return signal from all of the sets of Bragg grating sensors 241, 242, 243 because the sensor sets utilized the same
5 wavelengths. Therefore, each of the sets requires the same wavelength selective filtering and wavelength or phase discrimination equipment. Time division multiplexing techniques, disclosed for example in U.S. Patent No. 5,364,180, the disclosure of which is incorporated herein by reference, may be utilized to differentiate between the signals from each of the sets.

10

In addition to the use of a single reflective grating as a Bragg grating sensor 22, 23, 24, 25, (Fig. 2) as explained herein, an alternate embodiment of this invention can utilize a pair of reflective gratings within the same length of fiber, thus forming a resonant cavity of longer length. Such a resonant cavity will also reflect light of a
15 particular wavelength corresponding to a central wavelength of the reflective gratings. A change in the cavity length due to a static strain, a dynamic strain and/or a temperature induced strain on fiber will result in phase shift in the reflected light due to the change in optical path length within the reflective cavity. Such a device, termed a Fabry-Perot interferometer, can then provide a high sensitivity means of detecting
20 strain in the optical fiber, and the resultant optical phase shift can be detected using standard interferometer instrumentation techniques. Thus, it is possible with this technique to realize a Bragg grating sensor which has enhanced sensitivity. Alternatively, the pair of Bragg gratings may be used to form a lasing element for detection, for example by positioning an Erbium doped length of optical fiber between
25 the pair of Bragg gratings.

I claim:

processing means including wavelength selective filtering means for selectively filtering each one of said sensing light signals based on said respective bandwidth of each one of said Bragg grating sensors.

5 6. Apparatus according to claim 2, characterized in that said at least one optical sensor group includes a plurality of optical sensor groups, each group including a plurality of Bragg grating sensors, said apparatus further characterized by optical signal processing means for processing said respective sensing light signals from said Bragg grating sensors, said optical signal processing means having wavelength
10 division multiplexing means for differentiating between signals from individual Bragg grating sensors within one of said plurality of groups, said optical signal processing means having time division multiplexing means for differentiating between signals from Bragg grating sensors in different groups.

15 7. Apparatus according to claim 1, characterized in that a distal end of said optical fiber is terminated in an anti-reflective manner.

20 8. Apparatus according to claim 1, characterized in that said optical fiber is provided in a loop and wherein each one of said Bragg grating sensors reflects a portion of said input light signal having a frequency about said central wavelength; a remaining portion of said input light signal not reflected by any of said Bragg grating sensors being transmitted the entire length of said optical fiber.

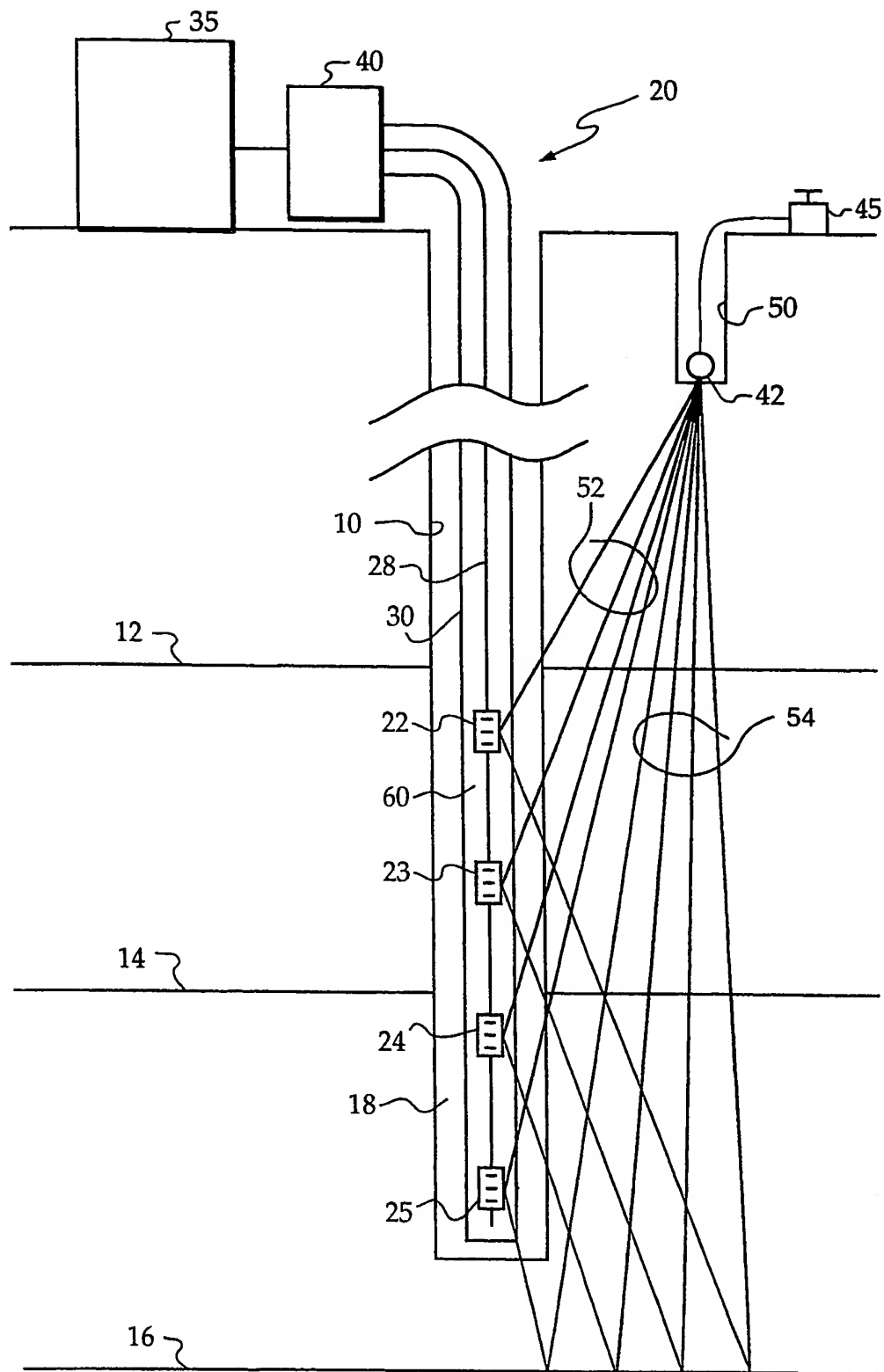
25 9. Apparatus according to claim 1, further characterized by optical sensing means responsive to said remaining portion for providing a signal indicative of the integrity of said optical fiber.

30 10. Apparatus according to claim 1, characterized in that said input light signal is provided to said Bragg grating sensors when they are in an equilibrium static strain and temperature strain condition, such that variations in said respective sensing light

location.

15. Apparatus according to claim 14, characterized in that each one of said Bragg grating sensors are tuned such that when subjected to a maximum static strain,
5 maximum dynamic strain and a maximum temperature strain, the maximum wavelength shift of said respective sensing light signal does not cause the frequency of said respective sensing light signal to enter the respective bandwidth of another one of said plurality of Bragg grating sensors.
- 10 16. Apparatus according to claim 15, characterized in that said input light signal is provided to said Bragg grating sensors when they are in an equilibrium static strain and temperature strain condition, such that variations in said respective sensing light signals are associated with dynamic strain caused by seismic signals.
- 15 17. Apparatus according to claim 16, further characterized by optical signal processing means for processing said sensing light signals, said optical signal processing means including wavelength selective filtering means for selectively filtering each one of said sensing light signals based on said respective bandwidth of each one of said Bragg grating sensors.
- 20 18. Apparatus according to claim 17, further characterized by a capillary tubing structure, said optical fiber being deployed in said capillary tubing structure to thereby protect said optical fiber from environmental conditions.
- 25 19. Apparatus according to claim 15, further characterized by optical signal processing means for processing said sensing light signals, said optical signal processing means including wavelength selective filtering means for selectively filtering each one of said sensing light signals based on said respective bandwidth of each one of said Bragg grating sensors.

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**FIG. 1**

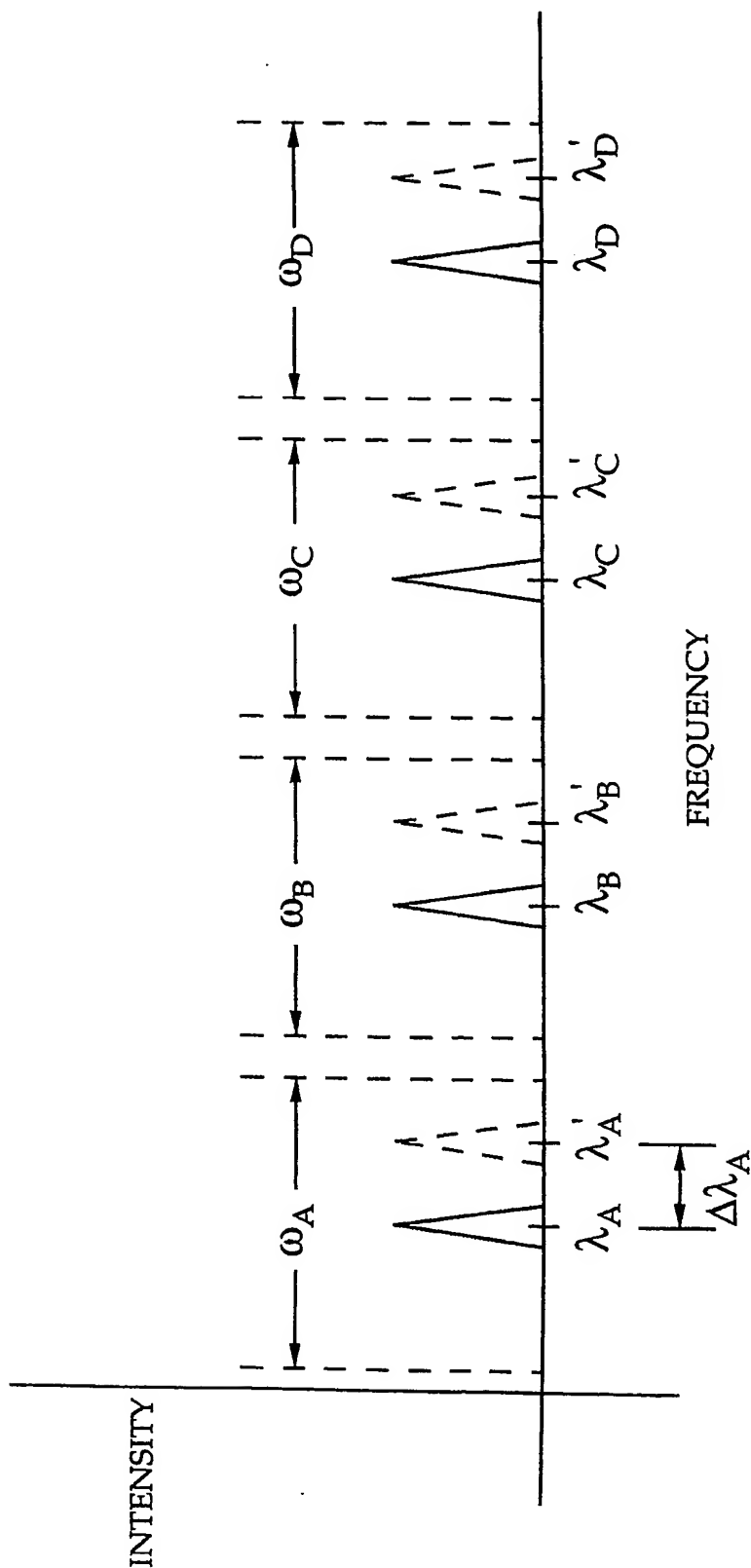
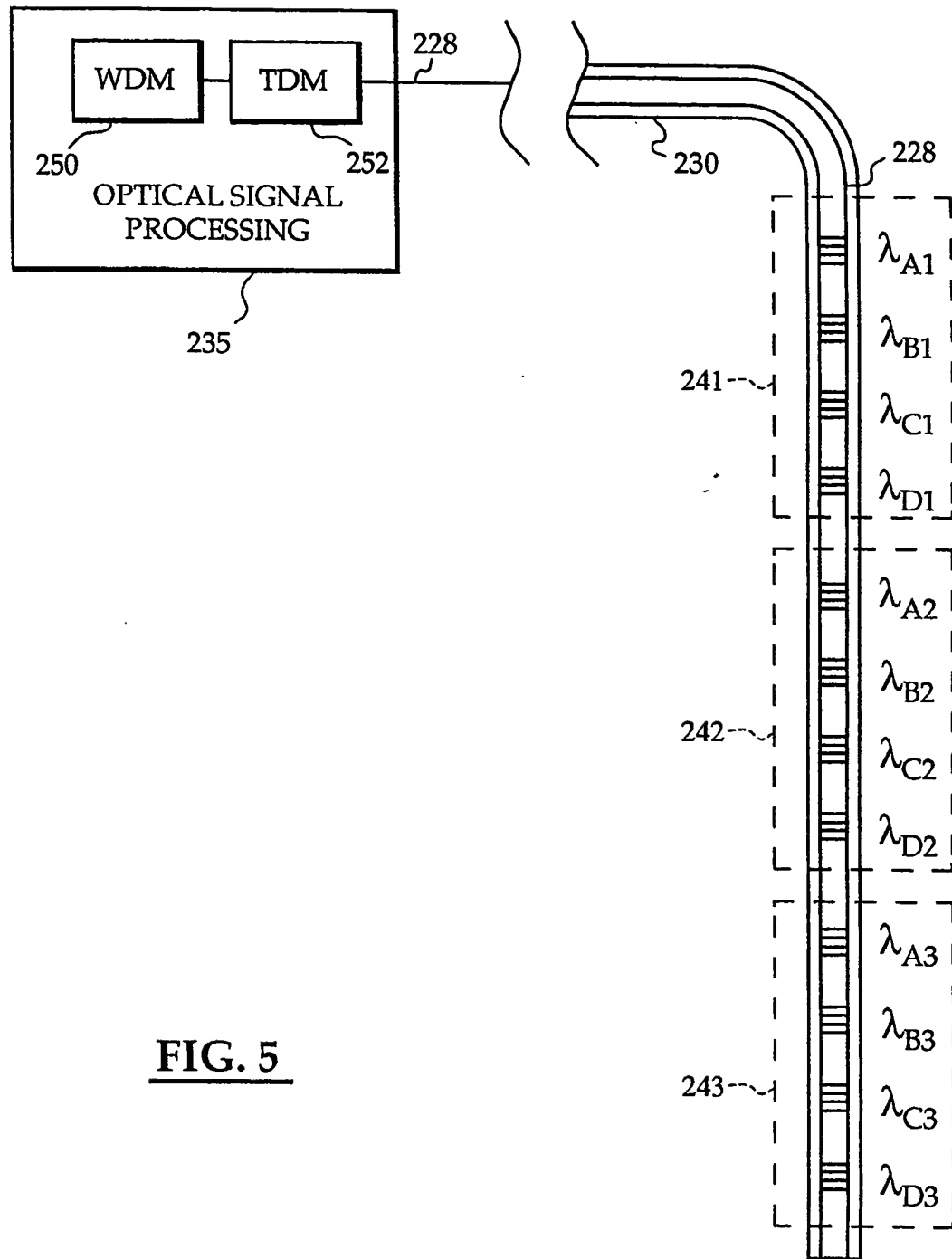


FIG. 3

**FIG. 5**

INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 98/02620

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

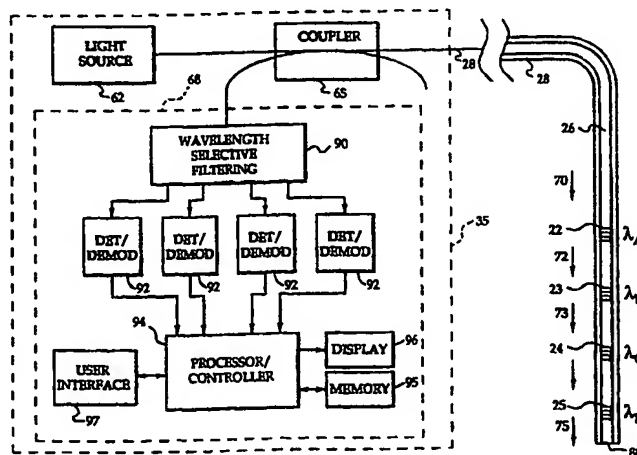
Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,Y	US 5 680 489 A (KERSEY ALAN D) 21 October 1997	6,13
A	see abstract; figures 1,4 see column 6, line 27 - line 32 ---	1-3,5
Y	US 4 313 185 A (GENERAL ELECTRIC) 26 January 1982 see column 3, line 11 - line 15; figure 1 ---	4,11,18, 20
Y	US 4 745 293 A (CHRISTENSEN DOUGLAS A) 17 May 1988 see abstract; figures 1,3,4	7-9
A	see column 3, line 59 - column 4, line 10 ---	1,2,9, 14,15
A	US 4 360 272 A (SCHMADEL DONALD ET AL) 23 November 1982 see abstract see column 10, line 1 - line 52 ---	1,14
A	US 5 497 233 A (MEYER A DOUGLAS) 5 March 1996 see column 1, line 24 - line 24 see column 7, line 16 - line 44 -----	6,13



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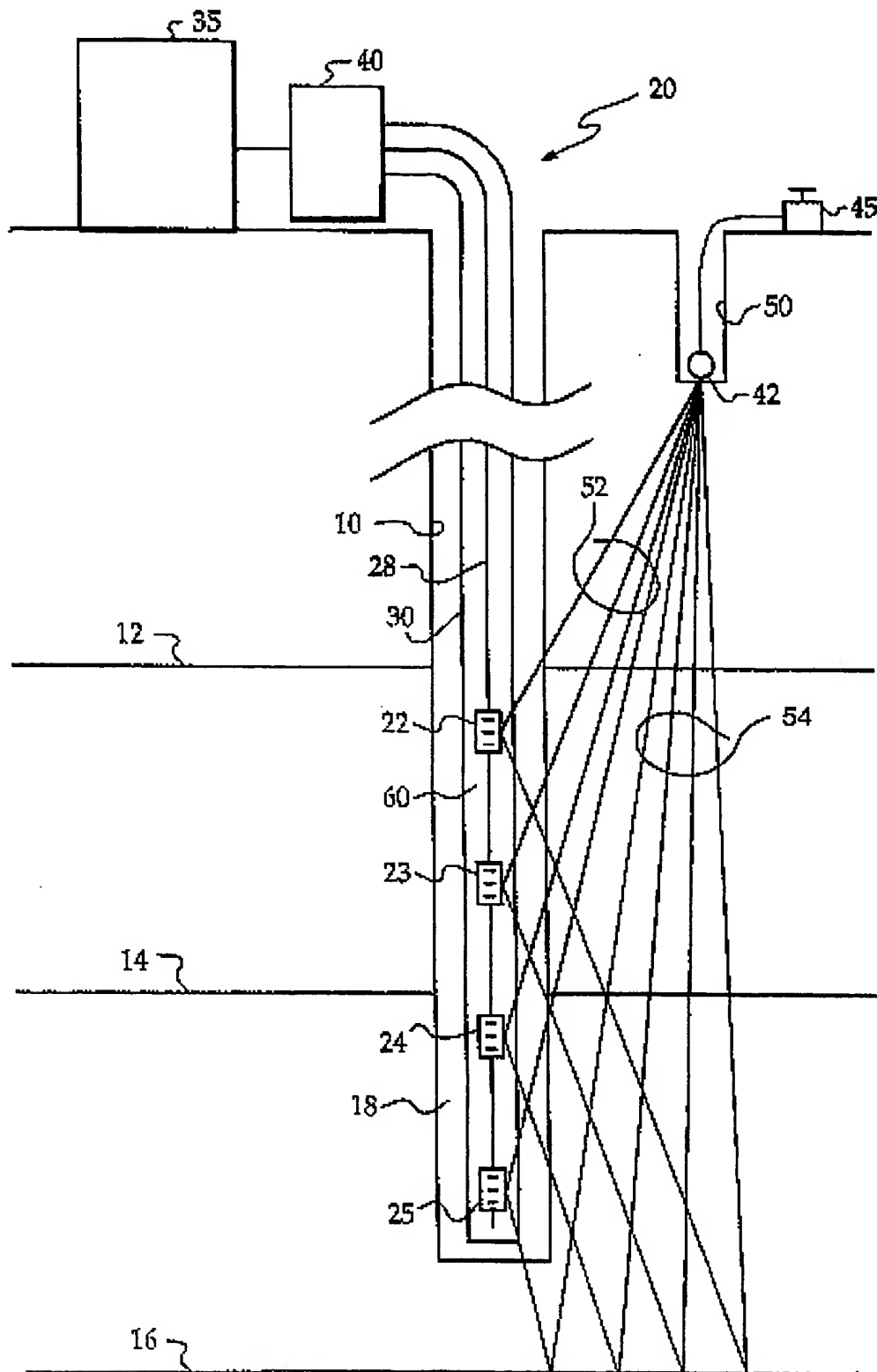
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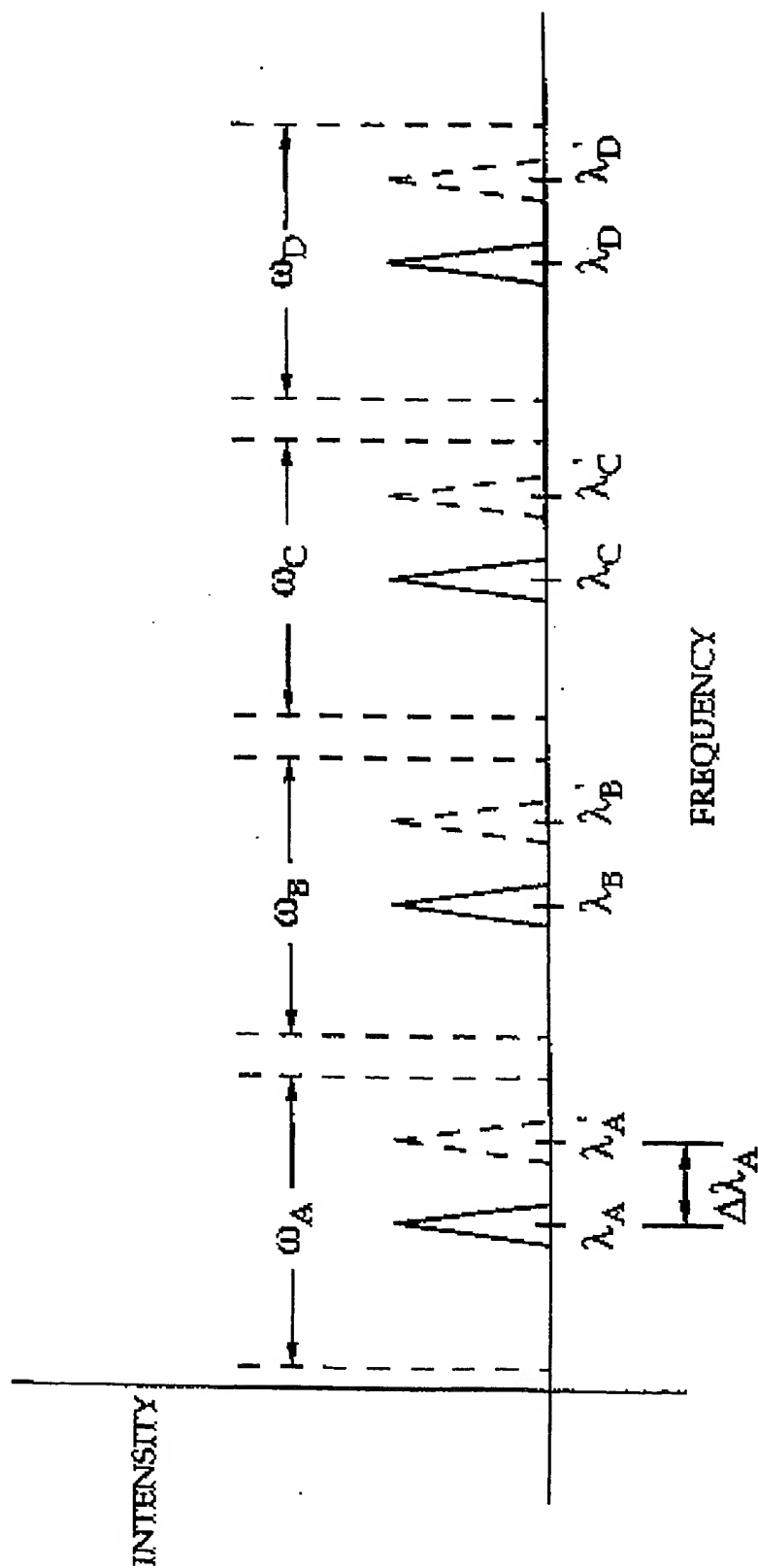
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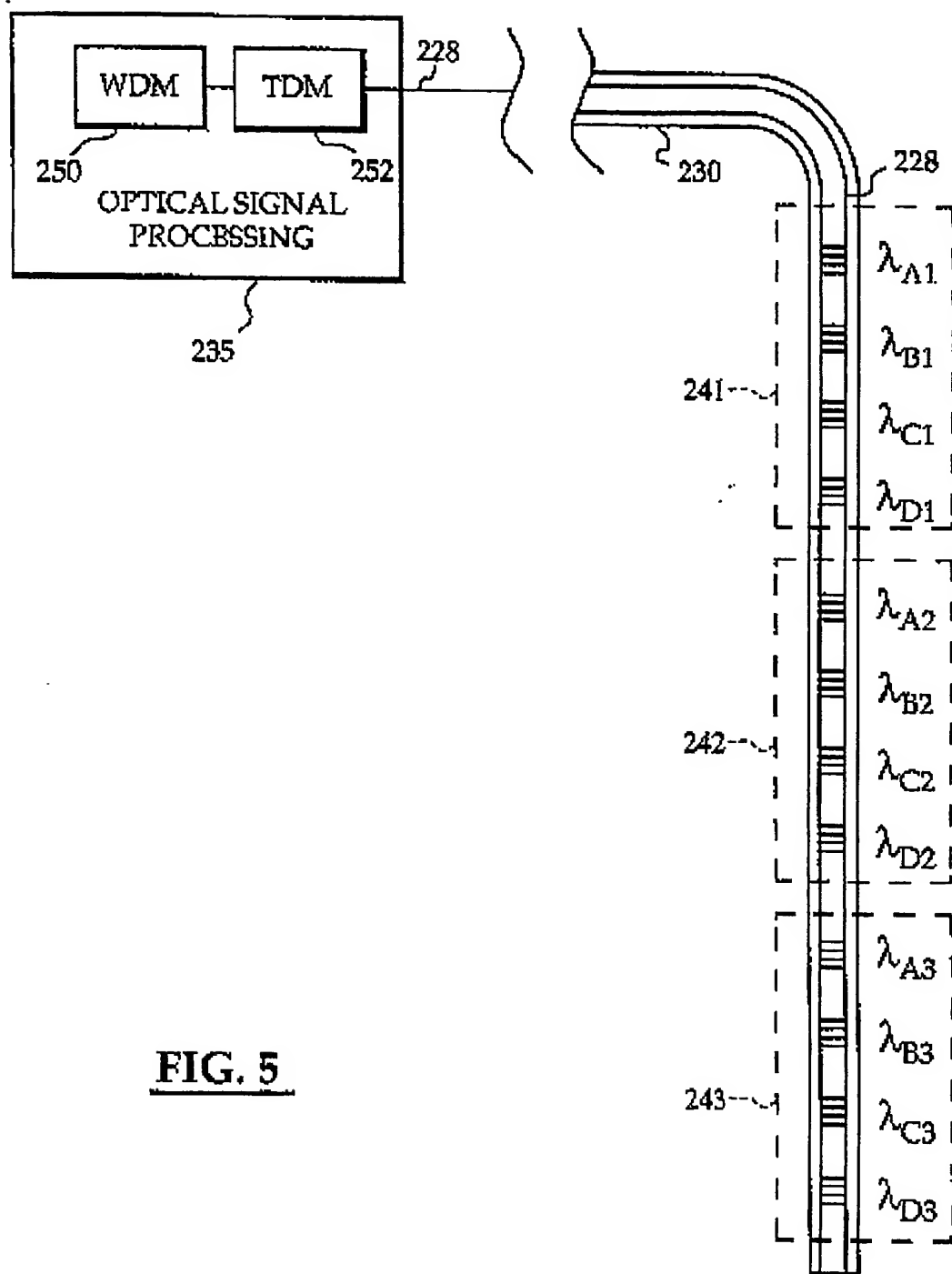


(57) Abstract

A system for vertical seismic profiling of an earth borehole includes an optical fiber (28) having a plurality of Bragg grating sensors (22-25) formed therein, each one of the Bragg grating sensors (22-25) being tuned to reflect a respective bandwidth of light, each bandwidth having a different respective central wavelength. Each of the Bragg grating sensors (22-25) are responsive to an input light signal, a static strain, a dynamic strain and a temperature strain for each providing a respective light signal indicative of static and dynamic forces and temperature at a respective sensor location. The physical spacing and wavelength spacing of the Bragg grating sensors (22-25) are known such that each of the sensing light signals are easily correlated to a specific depth. The Bragg grating sensors (22-25) are tuned such that when a sensor is subjected to a maximum static strain, maximum dynamic strain, and a maximum temperature strain, the maximum wavelength shift of a respective sensing light signal does not cause the frequency of the sensing light signal to enter the bandwidth of another one of the plurality of Bragg grating sensors (22-25).

**FIG. 1**

FIG. 3

**FIG. 5**